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Physical, Chemical, and Biological Conditions Associated With the Early Stages of the Lake Michigan Vernal Thermal Front

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ABSTRACT: An investigation of the thermal front in southeastern Lake Michigan during April 1988 revealed a dynamic physical, chemical, and biological environment. The front was observed approximately 4 km from the coast as a distinct gradient separating cold open-lake waters from warmer nearshore waters. Surface isotherms near the front were generally parallel to one another but skewed with respect to shore. Comparison between April 22 and 29 showed that the surface isotherm pattern was modulated by wind stress. The pattern from April 29 showed signs of flow instabilities with horizontal scales of 1 km to 5 km. Surface drifter trajectories provided estimates of horizontal convergence at the front which varied from $7 \times 10^{-6}\ s^{-1}$ to $20 \times 10^{-6}\ s^{-1}$. Inferred rates of downwelling, which ranged from 9.5 m d^{-1} to 20.7 m d^{-1}, were sufficient to move a water parcel from the surface to the bottom in 2 d to 6 d at the front. Convergent circulation was observed on both sampling dates despite contrasts in wind stress. Concentrations of chloride, soluble silica, and chlorophyll, which were always higher inshore, were 5% to 82% larger than offshore mean values. The aquatic environment just inshore of the thermal front was characterized by chlorophyll concentrations which exceeded 5.0 $\mu g\ l^{-1}$ while concentrations offshore were between 1.0 $\mu g\ l^{-1}$ and 2.0 $\mu g\ l^{-1}$. A relatively uniform vertical structure in chlorophyll concentrations in the frontal zone was consistent with the observed convergence and inferred downwelling near the front.

Introduction

The spring transition in large lakes from weakly stratified winter conditions to strongly stratified summer conditions is characterized by formation of a coastal thermal front (Boyce 1974; Csanady 1978). This transition, which occurs from April through June in the Laurentian Great Lakes, is dominated by high gradients in the temperature, nutrient, and plankton fields associated with the front. Similar to many temperate estuaries, a combination of solar warming, boundary heat flux (spring runoff), coastal bathymetry, and surface

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wind stress causes a frontal system to develop (Tikhomirov 1963; Rodgers 1966, 1968; Saylor et al. 1981). Initial warming, which is primarily due to river runoff, begins in shallow, nearshore waters where the offshore edge of the frontal system is marked by a nearly vertical 4°C isothermal surface separating cold offshore water from warmer inshore water.

Persistent frontal structures in fluid media normally require a convergent circulation to sustain them because large spatial gradients tend to be diminished by mixing processes. Due to the morphometry and the thermal mass of each Great Lake, and the nature of the heating processes, each basin primarily warms from the edges inward. As the near freezing water warms to 4°C, the temperature of maximum density for fresh water, the edge-wise warming process leads to formation of water with maximum density. As this dense water sinks to the bottom, adjacent surface waters converge and promote the juxtaposition of cold ($T < 4$°C) offshore and warmer ($T > 4$°C) inshore waters at the thermal front. If the surface convergence rate is greater than the natural dispersion rate for fluid parcels in this environment, then the frontal system sustains itself.

Repeated observations of frontal systems and simple scaling arguments indicate that limnological vernal fronts can persist up to 90 d (Huang 1969, 1972). The associated surface convergence and diffusion velocities are comparable and of the order of 1 cm s^{-1} (Okubo 1980). In the Great Lakes, the vernal front progresses from shore to the center of the lake at a rate of 0.5–1.0 cm s^{-1} (Scavia and Bennett 1980). Although this progression has traditionally been viewed as a thermodynamic process, the broader view indicates that nearshore surface waters physically "follow" the frontal zone lakeward. As these nearshore surface water parcels evolve when they move offshore, they promote enhanced primary production and subsequent higher trophic level interactions (Davis et al. 1980).

Maximum flows and high concentrations of suspended materials, dissolved organic matter, and dissolved nutrients are vernal characteristics of the rivers in the Great Lakes basin (Schelske et al. 1980; Moll and Brahce 1986). The consequences of the heightened riverine inputs are several; nearshore areas become chloride- and nutrient-enriched (Davis et al. 1980; Chang and Rossmann 1988), with gradients in most suspended and dissolved materials observed across the front (Rossmann 1986). Injection of algae from river runoff into the nearshore zone may serve as a "seed" population for a phytoplankton bloom immediately inshore of the front (Bowers et al. 1986). Phytoplankton blooms associated with the thermal front are at first con-

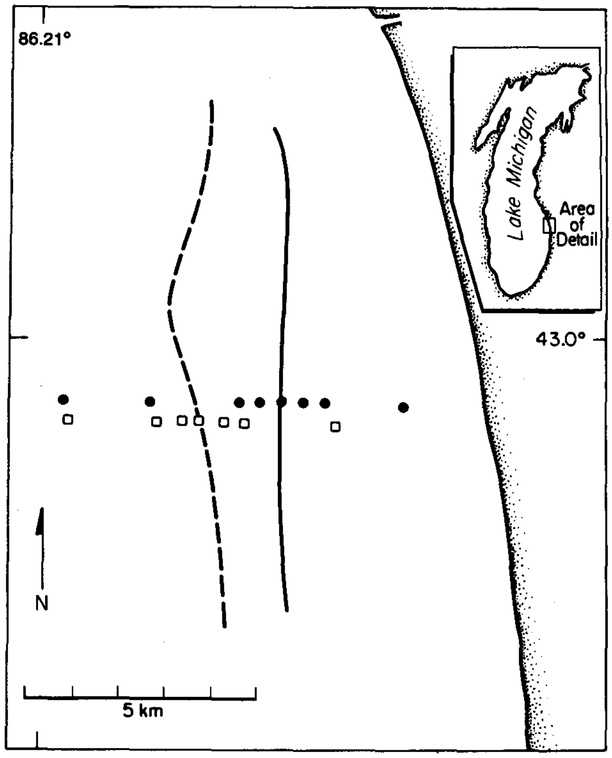

Fig. 1. Sampling site in southeastern Lake Michigan with 4°C isotherm and EBT/water chemistry stations from April 22 and 29 indicated on map. Solid line and dark circles are isotherm and stations from April 22. Dashed line and open squares are isotherm and stations from April 29.

fined to nearshore waters but then move offshore as the front migrates at a rate that approaches 1 km d^{-1} toward the end of the spring transition period (Stoermer 1968; Scavia and Bennett 1980; Chang and Rossmann 1988). Field studies and satellite imagery have shown that the greatest concentrations of chlorophyll and phytoplankton cells are located at or just inshore of nearshore fronts (Moll et al. 1980; Moll and Brahce 1986; Mortimer 1988).

The processes described above that are associated with the early development stages of vernal thermal fronts in large temperate lakes have several similarities to those related to temperate North American estuaries. Temperate estuaries and the nearshore zone of large lakes are impacted by the influx of a large amount of river runoff. This runoff creates a distinct front or transition zone between the surface plume of river water and the receiving waters. One special form of the estuary, the hypersaline system, can have physical conditions especially similar to limnetic vernal thermal fronts (Pagès et al. 1987). The material presented below discusses several salient aspects of thermal fronts in large lakes and then draws comparisons to estuarine frontal systems.

Using a combination of new field data and historical information, this paper examines two questions related to freshwater vernal fronts. These questions address the relation of the physical variability and structure of the frontal system to the distribution of dissolved and suspended matter in the vicinity of the front.

What are the surface thermal fields and currents in the immediate vicinity of the front? Although the outer edge of the frontal system is marked by the 4°C surface temperature, there is a finite width and structure to the system. To date, the detailed structure and variability ranges for the velocity and temperature fields are poorly quantified even though they help determine the chemical and biological properties of the frontal system.

Are the distributions of chemical and biological properties consistent with the observed physical variability? Property exchange near the frontal boundary appears to be an important aspect of the frontal system. To date, only one field and one modeling study address this aspect of Great Lakes frontal systems. The results of the study reported here are unique in that many of the important fields (physical, chemical, and biological) are measured such that they were co-located in time and space so that they could be quantitatively related.

Methods

Study Area and Sampling Approach

The sampling site was centered 10 km south of the mouth of the Grand River on the eastern side of Lake Michigan (Fig. 1). Prior studies have shown that the timing of the spring thermal front is relatively consistent in this area (Moll and Brahce 1986; Chang and Rossmann 1988; Mortimer 1988). The sampling was conducted on April 22 and 29, 1988, and consisted of three components. First, the thermal front was located and mapped using temperature observations to determine spatial structure. Second, surface current characteristics near the front were determined from drogue studies to estimate advection and convergence rates. Third, distributions of dissolved and suspended materials were determined from samples collected from a transect of stations oriented normal to the thermal front to elucidate gradient structure.

Thermal Fields

Surface water temperatures were measured to the nearest 0.1°C using a towed thermistor (Hydrolab Marine Thermometer T4). The average towing rate was 7.5 knots. Temperature readings were taken approximately once per minute within 5 km of the front and once per 5 min farther from the thermal front to yield at least 100 temperature readings on each sampling date. Temperature values were plotted on a navigational chart using Loran C coordinates (in the study area this represents positioning to within 20 m). These readings yielded a contour map of surface temperatures.

Vertical temperature structure was determined by repeated measurements with an EBT (TSK Micom BT). Thermal profiles were determined at the front and at stations 0.5, 1.0, 3.0, and 5.0 km on either side of the front. Temperature was measured to the nearest 0.1°C at 0.5-m intervals from the surface to the bottom.

Drogue Study

Five drogues were deployed to estimate surface currents and rate of convergence in the vicinity of the thermal front. The drogues were set in a pattern of two triangles, with an apex of each triangle adjoining the thermal front. The front location was determined from the surface temperature fields and subsequently marked with an anchored buoy. "Window shade" drogues consisted of a 1-m^2 "sail" area extending from about 0.3 m to 1.3 m below the surface. Each drogue was ballasted and attached to a spar buoy with minimal windage. Drogues drifted for approximately 8 h and then were retrieved. The time and Loran C position of release and retrieval were recorded for each drogue. The relative positioning errors associated with timing were negligible. Overall relative positioning errors were 1–3%.

Hydrodynamic Model

Convergance and downwelling rates were estimated from sequential locations of all five drogues using a simple flow model. The model used to estimate average downwelling rates from drogue movements is based on the continuity equation (mass conservation) for an incompressible fluid:

$$\mathrm{div}\ \bar{v} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad (1)$$

where x = (x, y, z) and v = (u, v, w) are the position and velocity vectors in a coordinate system fixed in space with coordinates increasing toward the east, north, and upward. Integration of Eq. 1 over a control volume is equivalent to integrating the velocity component normal to the surface of that volume over the entire surface. The control volume employed is cylindrical with the depth (axial length) equal to half the local water depth and the cross-sectional area equivalent to the area occupied by the drifter set. Assuming the simplest possible velocity structure (linearly varying velocity components and w = 0 at the free surface) either integration can be performed to yield:

$$\bar{w}_d = -d\left\{\frac{1}{A_0}\int_A\int\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)dA\right\} \qquad (2)$$

This equation shows that the average upwelling velocity, w, at control depth, d, is proportional to the average horizontal divergence (convergence) rate. The proportionality constant is −d, minus the control depth. $\bar{w}_d$ is an estimate of the near maximal downwelling speed at mid-water depth.

Meteorological Observations

Meteorological readings (wind speed and direction, air temperature, relative humidity, and barometric pressure) were taken from instruments on the research vessel. Readings were made at least three times throughout the 12-h sampling period on each sampling date. Wind speed and direction were recorded on an hourly basis.

Water Chemistry and Chlorophyll Measurements

Two stations were sampled for water chemistry and chlorophyll on April 22 and four on April 29. On both dates one station was sampled 1.0 km inshore and one was 1.0 km offshore of the thermal front. The two additional water chemistry stations, sampled on April 29, were at the thermal front and 0.5 km inshore of the front. Samples for water chemistry and chlorophyll were collected at 1-m depth and at subsequent 5-m intervals at each station. Water samples were collected in 5-l Niskin bottles and processed immediately. Chemistry samples were filtered through an HA Millipore filter (0.45 μm effective pore size), placed into small plastic bottles, and refrigerated. These 250 ml samples were analyzed for soluble silica (Strickland and Parsons 1972), nitrate-nitrogen (Armstrong et al. 1967), and chloride (United States Environmental Protection Agency 1976) with an Autoanalyzer II system. Chlorophyll samples were processed by filtering 1 l of lake water through a GF/C filter, placing filters into 5 ml of 90% acetone/water mixture (v/v) with a trace amount of $MgCO_3$, followed by grinding the filters. Ground filters were allowed to stand in the 90% acetone for 24 h, and the chlorophyll concentrations measured on a Turner Designs model 10 fluorometer.

Results

Thermal Fields

Isotherms on April 22 were roughly parallel to one another but converged toward shore farther north (Fig. 2). Consequently, the thermal front was

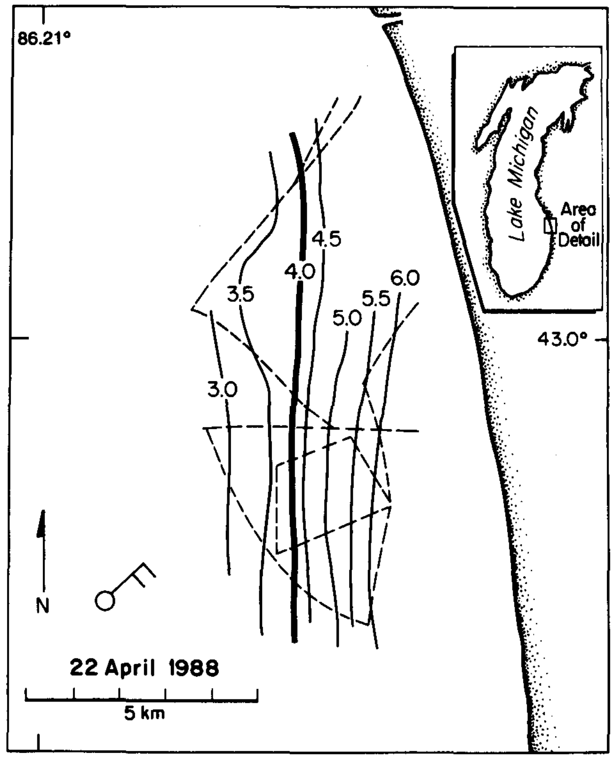

Fig. 2. April 22 surface isotherms. Dashed line indicates track of ship while measuring water temperatures.

4.7 km offshore at the southern end of the sampling area and 2.8 km offshore at the northern end of the sampling area. Surface water temperatures within 2 km of shore reached 6°C by April 22, while offshore of the front the temperatures remained below 4°C over the entire water column. Winds immediately preceding the April 22 sampling period were light and directed toward the southwest. During sampling the winds remained toward the southwest but increased in speed up to 10 m s^{-1}.

One week later, the thermal front remained in approximately the same coastal orientation, but the adjacent surface isotherm patterns exhibited more structure (Fig. 3). Inshore of the front, high curvature features were formed by the surface 4.5°C and 4.6°C isotherms (Fig. 3). The scale range characterizing these features was 1–5 km. Shore-parallel isotherms were observed within 3 km of the coast and offshore of the front. The maximum surface water temperature in the study area was 6.8°C. The front had moved approximately 1.2 km toward the center of the lake during the week and was found between 4.0 km and 5.6 km offshore (converging toward shore in the northern end of the sampling area). Winds just before and during April 29 were toward the southwest and stronger

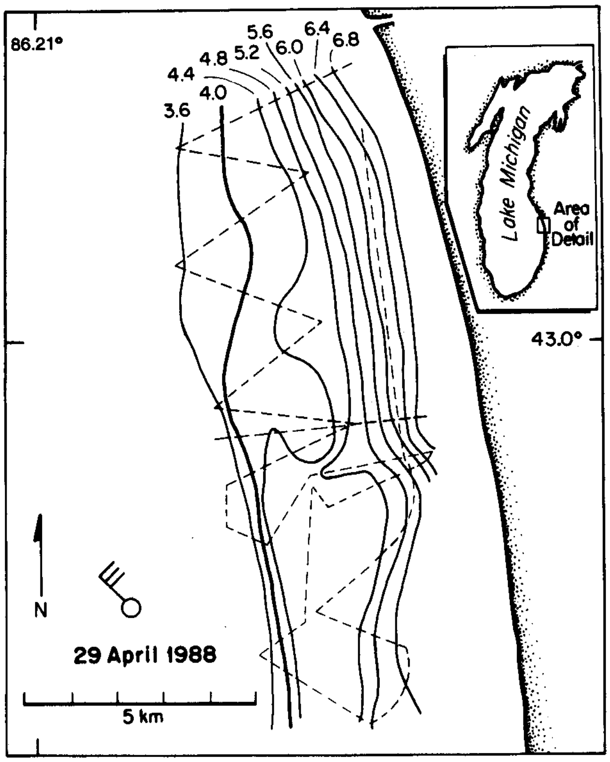

Fig. 3. April 29 surface isotherms. Dashed line indicates track of ship while measuring water temperatures.

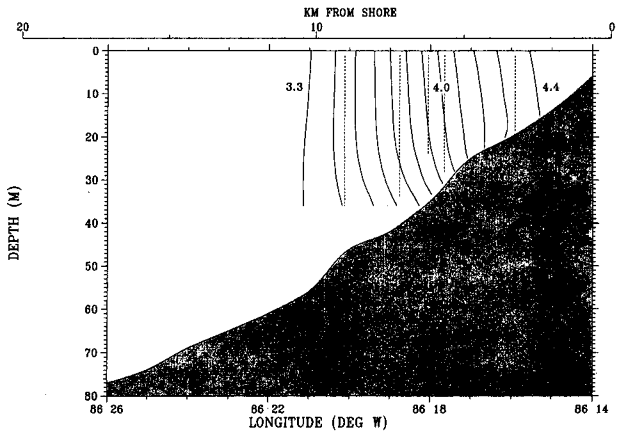

Fig. 4. April 29 temperature transect and bathymetry for sampling line at ~42°59′N. Vertical dotted lines show profile locations.

than the previous week. Wind velocities typically exceeded 10 m s^{-1} and occasionally gusted to 15 m s^{-1}.

Temperatures immediately inshore of the 4°C surface on both April 22 and 29 ranged from 4°C to 5°C and were uniform from 5 m below the surface to the bottom. Surface waters at these stations were about 0.2°C warmer than at 5 m. Offshore of the front, temperatures were below 4°C with a small amount of negative thermal stratification; temperatures were about 0.1°C warmer at 30 m than at 5 m (Fig. 4).

Currents

The current regime in the vicinity of the thermal front was investigated using drogues deployed as shown in Fig. 5. Drogue movements were used to estimate surface current velocity, convergence rate, and downwelling rate. Although the movement of the drogues revealed dominantly wind-driven near-surface currents, convergence toward the thermal front was measured by drogue movements on both sampling dates. On April 22, the drogues moved toward the southwest at 5–8 cm s^{-1} aligned with surface winds with a definite convergence toward the front. The drogues were deployed in a similar

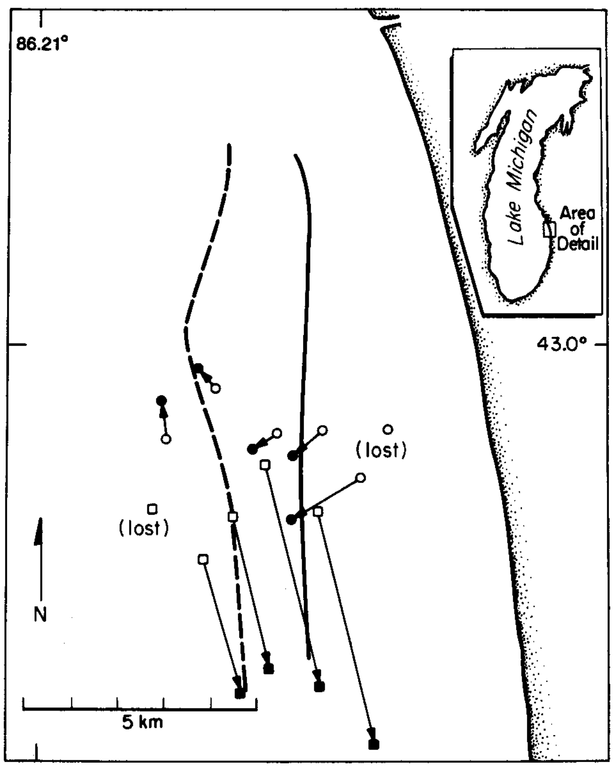

Fig. 5. Drogue movements and location of 4°C isotherm from April 22 (solid line) and April 29 (dashed line). Open circles are starting position of April 22 drogues. These drogues were deployed at approximately 1100 hr and retrieved about 8 h later at locations indicated by solid circles. Drogues deployed at approximately 1030 hr on April 29 moved from locations indicated by open squares to locations shown by solid squares over the course of roughly 9 h. On each date, one drogue was lost.

TABLE 1. Vertical distribution of water temperature (°C), chloride (Cl^-), soluble reactive silica (SiO_2), and chlorophyll (Chl) at two stations 1.0 km inshore and offshore of thermal front. Samples from April 22, 1988.

	Inshore				Offshore			
Depth	Temp (°C)	Cl^- (mg l^{-1})	SiO_2 (mg l^{-1})	Chl (mg l^{-1})	Temp (°C)	Cl^- (mg l^{-1})	SiO_2 (mg l^{-1})	Chl (mg l^{-1})
1 m	4.14	14.7	1.73	5.14	4.09	10.8	1.19	2.40
5 m	4.17	13.9	1.71	4.96	4.08	10.6	1.15	2.27
10 m	4.17	13.3	1.41	3.78	3.99	10.7	1.12	1.77
20 m	4.19	12.8	1.49	3.73	3.94	10.4	1.11	2.32
30 m					3.92	10.6	1.17	3.36

configuration on April 29, and the drogues moved to the southeast at about 20–25 cm s^{-1}.

As mentioned earlier, relative timing errors were negligible and relative positioning errors were in the range 1–3%. The separation distance between drogues was also relatively large compared to the positioning error so the associated error for position differences (used in strain rate estimates) could be additive and are approximately twice the relative positioning error (2–6%). The actual observational uncertainty associated with the drogue measurements is small compared to the windage factors for the drogues themselves. Windage factors vary with drogue design. These "window shade" drogues have an associated windage factor of 10–30% (McCormick et al. 1985). The errors associated with first differences of velocity components (e.g., calculation of convergence/divergence) and drogue windage should not be additive because a larger scale wind field adds a consistent bias which is removed with differencing. Therefore, we estimate that errors in the convergence/divergence estimates are 30% or less.

The surface flow converged along the outer edge of the front (near the 4°C isotherm). The results showed that on April 22 the rate of convergence was approximately 2.4×10^{-5} s^{-1} and the estimated rate of downwelling was 0.24 mm s^{-1} or 20.7 m d^{-1}. This rate of downwelling was sufficient to move a water "parcel' from the surface to the bottom (20 m) in 2 d. The following week, the rate of convergence was smaller at approximately 7.46×10^{-6} s^{-1}, yielding a downwelling rate of 0.11 mm s^{-1} or 9.5 m d^{-1}. This rate of downwelling was sufficient to move a "parcel" of water from the surface to the bottom (30 m) in 6 d. The downwelling rates computed are the mid-water column maxima, as estimated by the simple hydrodynamic model described above. The advection time estimates assume that vertical velocity varies from this mid-water maximum to zero at the surface and bottom as per the flow model of Bennett (1971).

Dissolved and Suspended Materials

The distributions of dissolved and suspended matter covaried with the physical structure of the front. The results from both April 22 and 29 show that concentrations of chloride, soluble-silica, nitrate-nitrogen, and chlorophyll were all higher 1.0 km inshore compared to 1.0 km offshore of the 4°C surface. The contrast was most pronounced on April 22 (Table 1) when average chloride concentrations were 13.66 mg l^{-1} inshore and 10.63 mg l^{-1} offshore, a difference of 28.5% in the mean values. Likewise, nitrate-nitrogen varied from 0.501 mg l^{-1} inshore to 0.396 mg l^{-1} offshore of the thermal front. Soluble silica showed a similar but smaller trend. The largest contrast across the thermal front was for chlorophyll; inshore concentrations were almost twice the offshore values (Table 1). Most variables were uniformly distributed throughout the water column offshore of the front (Table 2). Chloride, for example, varied by only 0.4 mg l^{-1} offshore of the front while inshore of the front it varied by 1.9 mg l^{-1}. Similar distributions were observed for soluble reactive silica, with surface to bottom differences of 0.32 mg l^{-1} and 0.08 mg l^{-1} inshore and offshore of the front, respectively.

Contrasts across the thermal front in concentrations of chloride, soluble silica, and chlorophyll were also present on April 29 (Table 2). But, these contrasts were smaller than the previous week, perhaps due to the effects of intensified wind-forcing and consistent with the observed relatively weak

TABLE 2. Vertical distribution of water temperature (°C), chloride (Cl^-), soluble reactive silica (SiO_2), and chlorophyll (Chl) at three stations 1.0 km inshore of the front, at the front, and 1.0 km offshore of the front. Samples from April 29, 1988.

	Inshore				Front				Offshore			
Depth	Temp (°C)	Cl^- (mg l^{-1})	SiO_2 (mg l^{-1})	Chl (mg l^{-1})	Temp (°C)	Cl^- (mg l^{-1})	SiO_2 (mg l^{-1})	Chl (mg l^{-1})	Temp (°C)	Cl^- (mg l^{-1})	SiO_2 (mg l^{-1})	Chl (mg l^{-1})
1 m	4.45	9.95	0.84	2.05	4.40	10.7	0.99	2.35	3.22	9.69	0.87	1.82
5 m	4.44	9.95	0.85	2.23	4.34	10.7	1.05	2.12	3.19	9.85	0.91	2.04
10 m	4.43	9.99	0.86	2.17	4.27	10.6	0.98	2.42	3.20	9.81	0.89	1.69
15 m	4.42	10.0	0.83	2.30								
20 m					4.30	10.4	0.97	2.20	3.20	9.68	0.89	1.96
30 m					4.31	10.2	1.06	2.27	3.27	9.74	0.88	1.83

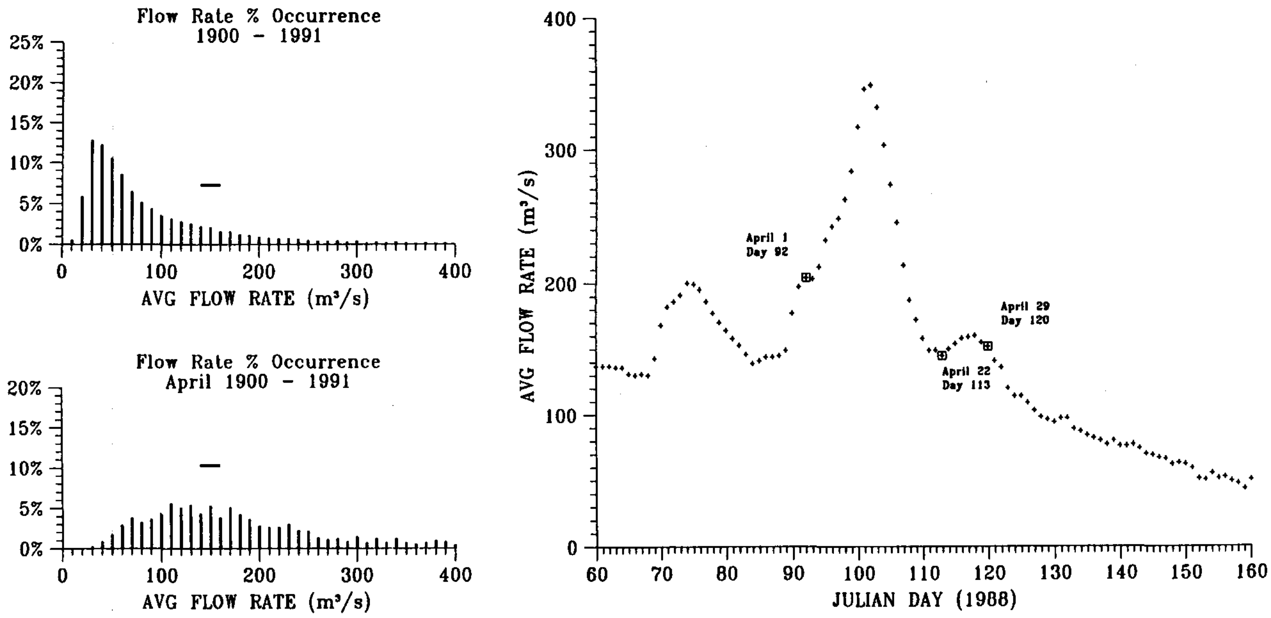

Fig. 6. Grand River daily average flow rate data. Left panels show frequency of occurrence histograms for period spanning 1900 to 1991. Overbars show ranges for survey period. Right panel shows time history of Grand River daily average flow rate data for spring 1988. Overbar spans interval shown in expanded format in upper right panel. Note that two-week period immediately preceding survey dates is one of anomalously high flow rate.

horizontal flow convergence. For example, average chloride concentrations were approximately 10.28 mg l^{-1} inshore compared to 9.75 mg l^{-1} offshore of the thermal front, leaving a net difference of only 0.53 mg l^{-1}. This difference of 6% is less than the 30% difference observed the previous week. Similar to the chloride distribution, smaller differences across the thermal front were observed on April 29 in mean concentrations of soluble silica and nitrate-nitrogen (Table 2). The distribution of chloride, soluble reactive silica, and chlorophyll on April 29 showed much smaller contrasts both across the front and with depth (Table 2) compared to the previous week. For example, chloride varied by no more than 0.5 mg l^{-1} from the surface to bottom at stations 1.0 km inshore or offshore of the front or at the front. Likewise, the vertical variation in the concentrations of soluble reactive silica and chlorophyll was relatively small. The highest average concentrations of all three variables were found at the front compared to offshore and inshore of the front.

Discussion

River Runoff and Wind Stress

Early in the evolution of the vernal thermal front, river runoff is usually the primary source of heat, with temperature differentials of 5°C to 10°C occurring between river runoff and lake water in early spring. Heat flux estimates based on typical values of riverine mass flux ($>10^7$ m^3 d^{-1}) and river-to-lake temperature contrast of 5–10°C for southeastern Lake Michigan suggest that in the early spring riverine input is a prime source of nearshore water warmer than 4°C. This warm, buoyant coastal water can drive a convergent surface circulation which in turn effectively transports chloride, nutrients, and particular substances, such as fine sediment and phytoplankton, from nearshore areas lakeward. In the early development stages of the front, the volume of warmed coastal lake water is comparable to the integral flux of river water into the lake basin.

Figure 6 shows time series and frequency of occurrence data for the major river source near our study area. These data illustrate typical flow rates for the annual cycle and for the month of April only, and how flow rates in our specific sampling interval compare to the longer term rates. "Fill-time" estimates for a nearshore coastal wedge (of dimensions 10 km × 3 km × 15 m) are of the order 30 d. This suggests that river inflow exerts a significant influence on these coastal waters especially if important environmental constituents are more concentrated in river waters. For example, if a riverine constituent has a perturbation value 10 times greater than the range observed in coastal waters, a first-order change in coastal values can be induced by a few days of riverine input.

The importance of the heating from spring runoff varies on an interannual basis depending on the relative amplitude and phasing of the major period of runoff with the direct solar warming of surface waters. Rossmann (1986) found in southeastern Lake Michigan that during some years the nearshore waters warmed more slowly, suggesting a lesser contribution from river runoff; remarkably, in 1975, a thermal front was not observed in southeastern Lake Michigan (Rossmann 1986). As the thermal front becomes established in the mid-spring, direct solar insolation begins to dominate the thermal regime because streamflows are diminished from their annual maximum and the increasing volume of water between the front and nearshore lessens the relative impact of heat input from runoff.

Warming from solar insolation and river runoff tends to determine the basic thermal regime, sets the speed of the migration of the front, and forces the formation of average circulation patterns (Bennett 1971; Rodgers 1987). However, wind stress may have an effect at somewhat smaller scales as can be inferred from a comparison of frontal structure on April 22 and 29. On both dates the same general structure was observed and the front was found in approximately the same orientation with respect to the shore although the front had migrated 1.2 km farther offshore in one week. This progression rate is considerably lower than the average rate ($\sim$1 km/d^{-1}) required over the full warming period. These results indicate that sustained and increased wind stress can significantly alter the surface thermal regime adjacent to the front.

The temperature structure observed during higher winds suggests the possibility of frontal instabilities similar in character and scale to those anticipated by Huang's (1969, 1972) frontal stability studies. These instabilities will enhance cross-frontal exchange and mixing which in turn can induce downwelling (due to the formation of 4°C water) and enhance vertical transport (downward) of near-surface dissolved and particulate constituents. Heat is efficiently transported from coastal waters lakeward, but there is relatively little vertical heat transfer in the frontal region proper because the downwelling zone of the frontal region is weakly stratified with respect to temperature and density. Figure 5 illustrates the possible importance of horizontal (versus vertical) flux components.

One remarkable aspect of this circulation regime is that it is potentially self-sustaining once initiated as long as a horizontal temperature differential exists across the 4°C surface. That is, further surface or nearshore heating or wind mixing/stirring is not required once the convergent/downwelling process begins. This accounts, to some degree, for the observed persistence of structure associated with this particular type of front. Ultimately, heating/cooling mechanisms must act to maintain the cross-frontal temperature gradient. Zilitinkevich et al. (1992) show that flow convergence and subsequent heat transfer into the frontal zone is an important transport mechanism.

Distribution of Dissolved and Suspended Materials

The physical processes associated with the thermal front have an impact on the distribution of dissolved substances and suspended particles. As mentioned above, the initial development of vernal thermal fronts often coincides with the period of spring runoff in the Great Lakes basin. This runoff carries high concentrations of many dissolved materials, including chloride and nutrients (Schelske et al. 1980; Moll et al. 1991) that originate from road salt and nonpoint sources. The runoff tends to remain nearshore in the early spring creating a band of enriched water along the coast (Davis et al. 1980; Moll and Brahce 1986; Rossmann 1986). This sequence of events was evident in 1988 as the Grand River discharge was a recognizable plume with different optical characteristics. The plume was diverted to the right on April 22 as it entered the lake basin. This diversion toward the right was probably a response to a counter-clockwise flow along the edge of the basin which tends to be a large-scale feature of all the Great Lakes (Mortimer 1988). The general structure of the entrained river plume, with warmer, lighter water flowing counter-clockwise at the surface nearshore, is very similar to the expected "thermal bar" circulation which is usually attributed to direct solar warming of nearshore waters in the absence of riverine sources.

This study has shown that there are some impacts associated with the enriched runoff waters. Chloride, which served as a conservative tracer, showed high (13–14 mg l^{-1}) concentrations inshore of the thermal front with relatively uniform concentrations from the surface to the bottom (Table 1). Offshore of the front, chloride concentrations matched known mid-winter ambient lake levels (9–10 mg l^{-1}) (Rousar 1973). A similar pattern was observed on April 29, although the contrast in chloride concentrations across the front (10–11 mg l^{-1} inshore versus 9–10 mg l^{-1} offshore) was small compared to April 22 (Table 2). This chloride distribution is consistent with frontal convergent circulation patterns, indicated by the drogue measurements, which effectively transport nearshore constituents lakeward, and in the frontal region proper, from surface to deep basin waters. In

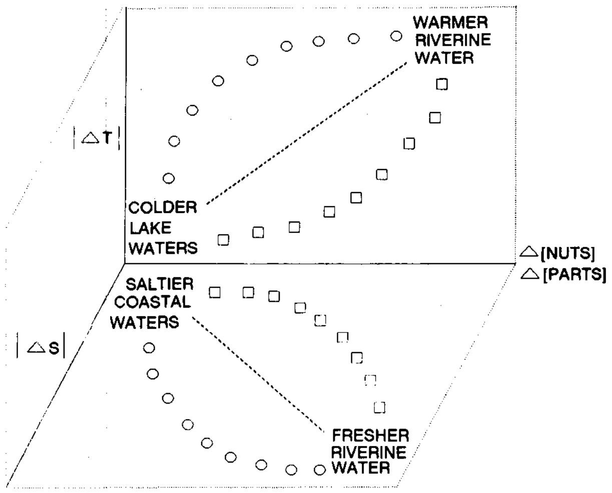

Fig. 7. Schematic water property diagram showing parallel aspects of riverine source water evolution in limnetic (top) and estuarine environments (bottom). In each case, mixing lines are shown with potential paths for active scalar fields with significant in situ source (boxes) or sink (circles) mechanisms.

the vicinity of the 4°C isotherm, density stratification is generally very weak (due to the fact that $\delta\rho/\delta T \approx 0$ for pure water). Here even small perturbations in dissolved chemical constituents (~ 1 mg l^{-1}) can have a stabilizing or destabilizing influence upon the density field. In Lake Michigan, the total range of temperature-induced density difference from 3.5°C to 4.5°C is equivalent to ~ 2 mg l^{-1}.

Observations by Rossmann (1986) in southeastern Lake Michigan showed this frontal pattern was a consistent feature during April from 1974 to 1982. The influence of river runoff was evident over this 9-yr span because nearshore chloride concentrations were always elevated over ambient mid-lake levels. In some years average chloride concentrations differed by 30–40% across the thermal front while in other years the difference was less than 5%, indicating the possible importance of the phasing of periods of high runoff to direct solar warming. The results from this study showed both extremes can occur at the same location separated by only 7 d. Therefore, concentrations of runoff-related constituents can modulate on relatively short time scales requiring both frequent sampling within any one year and interannual studies.

As the runoff wanes during the later stages of the spring transition (May and June in southeastern Lake Michigan), nutrient inputs derived from runoff become small and nearshore waters may become nutrient depleted as supplies of orthophosphorus and soluble silica are reduced by surface phytoplankton growth (Schelske et al. 1980). A pattern of relatively low nutrient concentrations immediately adjacent to the shore and higher concentrations adjacent to the thermal front has been observed (Mortimer 1988). This pattern can be realized if there is a nutrient source, such as cross-frontal exchange from nutrient-rich mid-lake water in the frontal region of a nearshore nutrient sink associated with phytoplankton growth.

The distribution of suspended materials in the nearshore zone is also highly impacted by the thermal front and associated current regime. Spring runoff carries high suspended sediment loads which contribute to a general level of nearshore turbidity (Chang and Rossmann 1988). This material, which is readily observable both from ships and remote sensing platforms, eventually reaches the front and contributes to the distinct color gradient observed near the thermal front. This process differs from the long-term evolution of nutrient fields because of differing source/sink mechanisms for suspended sediment. High phytoplankton biomass just inside the front also contributes to the color contrast.

Possible Influences of Thermal Fronts on Food Webs

Several previous studies have observed or speculated that the plankton, particularly the phytoplankton, are affected by the presence of the thermal front and the associated current regime (Scavia and Bennett 1980; Mortimer 1988; Franks 1992). The phytoplankton found adjacent to the thermal front in Lake Michigan is comprised mostly of diatoms with highest abundances typically found inshore and often immediately offshore of the front (Bowers et al. 1986; Rossmann 1986). The algae may have been provided favorable conditions for growth from the nutrient-enriched waters that are confined near the surface by nearshore thermal stratification extending inshore of the thermal front. Convergent flow may move these algae to the front and then below the surface. The frontal convergence and downwelling can also rapidly move plankton from the surface to the bottom where they may serve as an important source of food for the benthos. As the front moves offshore and riverine nutrients decline, cross-frontal exchange may become a source of nutrients for the phytoplankton. The results from this study do not provide enough information to confirm that this sequence of events occurred in April 1988. But, the distribution of chlorophyll on April 22, 1988, was compatible with the concepts described above. Highest chlorophyll concentrations were observed inshore of the 4°C surface and along the frontal boundary to the bottom (Table 1).

Comparison of Estuaries, Hypersaline Estuaries and Thermal Fronts

Both estuaries and nearshore zones of large lakes often are characterized by large influxes of river runoff. This runoff may be less dense than the receiving waters but for different reasons in each case. The runoff into the estuary is less saline and perhaps warmer while temperature is the primary factor determining density in the limnetic environment. Despite these differences, the primary response is that the less dense runoff floats on the surface and spreads in a buoyancy-driven flow. The runoff is usually confined to nearshore areas resulting in zones of high temperature/density/chemical gradients. Typically, the runoff is nutrient-enriched which promotes high chemical gradients across the fronts. Mixing processes tend to dissipate the nutrient gradients, but runoff serves to replenish the dispersed nutrients and sustains the gradients.

An illustration of conceptual parallels between riverine properties introduced into large lakes and estuaries is shown in Fig. 7. Prime properties contributing to a density anomaly in each case are associated with two orthogonal axes while a third orthogonal axis measures change in environmentally important scalar constituents such as dissolved nutrients (Δ[NUTS]) and suspended particulates (Δ[PARTS]). Generally speaking, riverine source waters contribute to local anomalies in density (temperature, salinity) and in other scalar fields. As river waters are mixed into the respective receiving waters the associated anomalies diminish. Passive scalar constituents "blend" along a mixing line. Fields with significant "sink" mechanisms diminish faster than pure mixing would allow (e.g., nutrient uptake by phytoplankton, particle settling, etc.). Fields with significant "source" mechanisms can sustain themselves, relatively speaking, as dilution through mixing progresses (e.g., phytoplankton growth and related particle production).

An interesting parallel can be drawn between thermal fronts in the Great Lakes and hypersaline estuaries, such as the Van Diemen Gulf (Wolanski 1988), the Casamance River (Pagès and Debenay 1987; Pagès et al. 1987), and the Lower Laguna Madre (Breuer 1962). These systems arise in part from intense rates of evaporation and minimal freshwater flow into the estuary. The most saline and dense waters are associated with hypersaline conditions in the central portion of the estuary. Small perturbations in the density field due to in situ processes can cause analog convergent circulations and "bottom water" formation. This process occurs in the offshore portion of the Great Lakes frontal zone mediated by larger scale horizontal mixing and stirring processes. In the Van Diemen Gulf, this occurs as a result of evaporative fluxes in the outer reaches of the gulf as estuarine waters make their way to the Arafura Sea. Both in the Casamance River and the Van Diemen Gulf, the densest water sinks to the bottom of the estuary causing surface convergence from each end of the estuary, much like the convergence induced by the sinking of 4°C water at the limnetic thermal front. These physical processes which are analogous to limnetic thermal fronts appear to create chemical gradients and zones of heightened productivity (Guillou et al. 1987; Le Reste and Collart-Odinetz 1987) which are also analogous to thermal fronts in large lakes.

Summary

The results from this study indicate that the chemical and biological fields associated with vernal thermal fronts in southeastern Lake Michigan directly covary with the physical features observed during the spring transition period. The major physical characteristics observed were as follows. A thermal front was readily observable by distinct color and temperature gradients. Surface isotherms generally ran parallel to one another and were modulated by surface wind forcing. In southeastern Lake Michigan, the thermal front was not strictly shore-parallel, but converged toward shore in the northern end of the sampling area. The front migrated approximately 1.2 km toward the center of Lake Michigan in one week. Surface currents converged at the front from the nearshore and offshore regions of Lake Michigan. The estimated surface convergence rate ($7–20 \times 10^{-6}\ s^{-1}$) implied a substantial frontal downwelling rate (ranging from $10\ m\ d^{-1}$ to $20\ m\ d^{-1}$), and surface temperature patterns or structure with horizontal scales of 1–5 km observed near the front were possible manifestations of flow instability.

These physical features appeared to have the following effects on the distribution of dissolved and suspended material. Spring runoff, which was enriched with nutrients and chloride, was advected toward the offshore edge of the frontal system by convergent current structure. Concentrations of nutrients and chloride were higher inshore versus offshore of the front. Significant gradients of dissolved and suspended materials were observed across the front. The aquatic environment just inshore of the thermal front was characterized by high chlorophyll concentrations (up to twice the offshore concentrations and from 3 to 10 times typical values observed at the surface during the mid-summer). The uniform vertical structure in chlorophyll concentrations at the front is consistent with convergence (directly observed) and downwelling (inferred from a simple flow model) in the flow field. The density perturbations associated with the chloride field were of sufficient magnitude (compared to temperature-related density effects) to induce instability in the density field at the outer edge of the frontal zone.

This study, combined with results and hypotheses put forward in other studies, suggests that the overall timing and detailed spatial structure of the vernal thermal front regime can be highly variable. The duration and timing of frontal development has an impact upon the density and composition of the springtime phytoplankton community. The spatial structure of the frontal regime may determine the magnitude of the associated horizontal or vertical fluxes of important physical, biological, or chemical properties and thus the relative contribution of energy to primary and secondary segments of the food web in different parts of the water column. The vertical transport of phytoplankton to deeper lake waters through frontal subduction may be one mechanism for controlling integral food web structure. The mechanisms regulating the formation and fluxes of particulates also have important implications with regard to the pathways and fates of toxic substances.

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